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THERMAL PERFORMANCE OF A POLYMERIC PULSATING HEAT PIPE

Marco Antonio Covielo
Cristiano Bigonha Tibiriçá
Heat Transfer Research Group, Escola de Engenharia de São Carlos (EESC) – University of São Paulo (USP) - Av. Trabalhador São-carlense, 400, Pq Arnold Schimidt, São Carlos - SP/Brasil, CEP 13566-590
marco.covielo@usp.br, bigonha@sc.usp.br

Abstract. *The objective of this work was the investigation of the heat transfer characteristics of pulsating heat pipes built using polymeric flexible materials. An experimental apparatus to obtain heat transfer measurement in polymeric pulsating heat pipes was developed. The heat transfer rate transmitted by the pulsating heat pipe was calculated through energy balance in the evaporator, using measurements of temperature variations in the water outside the evaporator. The internal fluid used in the pulsating heat pipe was R134a and the internal diameter was 2.0 mm. Type K thermocouples were used for temperature measurements along the heat pipe and for the energy balance of water outside the evaporator. The total thermal resistance for the pulsating heat pipe was calculated based on the temperatures differences between the evaporator and condenser, and the exchanged heat rate. The effect of orientation of the heat pipe in respect to the gravity field was also evaluated. As results, heat transfer rates up to 36 W was obtained with total thermal resistances of 0.8* ^{o}*C/W. The results showed the potential of applying flexible polymeric materials to build pulsating heat pipes which allows versatile heat exchanger design in applications with complex geometries.*

Keywords: *compact heat pipes, R134a, heat transfer, high conductivity*

1. INTRODUCTION

Pulsating heat pipes are passive compact devices that use evaporation and condensation forces to promote fluid flow. To operate in a stable manner the tubes used in pulsating heat pipes should have an inner diameter smaller than the Laplace diameter (Tibiriçá and Ribatski, 2013), with usually corresponds to diameter bellow 3 mm, which ensure the formation of liquid slugs. These devices do not need a separate capillary structure to promote liquid return and can operate in several orientations related to the gravitational field (Burbain et al, 2013).

With the recent development of micro-electronics and the ability to micro fabrication, new applications in electronics, refrigeration and aerospatial emerged and efficient techniques for refrigeration in micro-scale become necessary (Vasiliev, 2008). One of these techniques is the pulsating heat pipes, which are devices that allow heat transfer using phase change without the need of an active pump system, like pumps and compressors (Mameli et al. 2014). With these devices, heat is supplied with an evaporator been transported along the tube and rejected in the condenser.

The heat exchanges using heat pipes is a method that allows the achievement of an equivalent thermal conductivity above 1000 W/m.K, which is much higher than the common thermal conductors used in engineering applications (Chien et al 2012, Srimuang et al, 2012). This level of equivalent thermal conductivity values shows a high potential for the application of these heat exchangers, considering the simplicity, low cost and reduced dimensions.

In this context this work investigates the performance of a pulsating heat pipe built with polymeric tubular materials not yet tested and documented in the literature, using R134a as working fluid. The motivation of using polymeric materials is related with the low cost and also with the high elastic bending capacity of the material, allowing easily installation in final applications. The heat transfer rate, total thermal resistance and equivalent thermal conductivity of the pulsating heat pipe were measured for the developed device.

2. EXPERIMENTS AND METHODS

2.1 Experiment description

Figures 1 through 3 show the system used for tests. The experiments were performed with the use of two reservoirs, one filled with hot water (the evaporator) and another one with cold water (the condenser). The reservoirs were positioned at different vertical level through use of a screw as showed in Fig. 1. The internal diameter of the reservoirs were 110 mm.

The pulsating heat pipe is made of nylon flexible tube, having 3.30 mm of external diameter and 2.0 mm of internal diameter. This tube is filled with R134a and both ends were sealed together. In the first experiment, 1 m of the pulsated heat tube was inserted in the evaporator and 1 m inserted in de condenser as showed in Fig. 2. The evaporator reservoir was kept in the bottom and the condenser in the top. In the second experiment 5.50 m of nylon tube was inserted in each reservoir increasing the heat transfer area inside the reservoir.

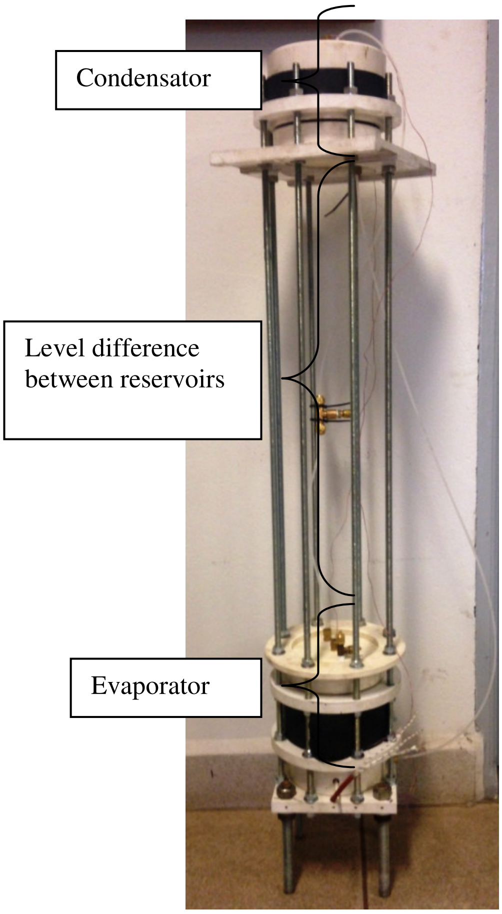

Figure 1. Configuration of the experiments

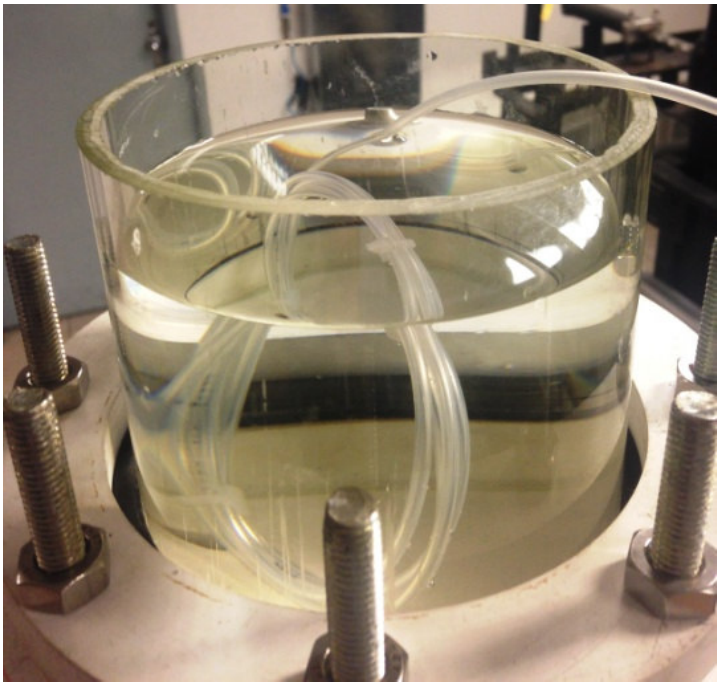

Figure 2. Pulsating heat tube inserted in the reservoirs

The mass of refrigerant inserted in the tube was measured with an electronic scale and the tube was filled with 70% of its volume with liquid refrigerant. After filling the nylon tubes with refrigerant R134a the reservoirs were closed and thermal insulated.

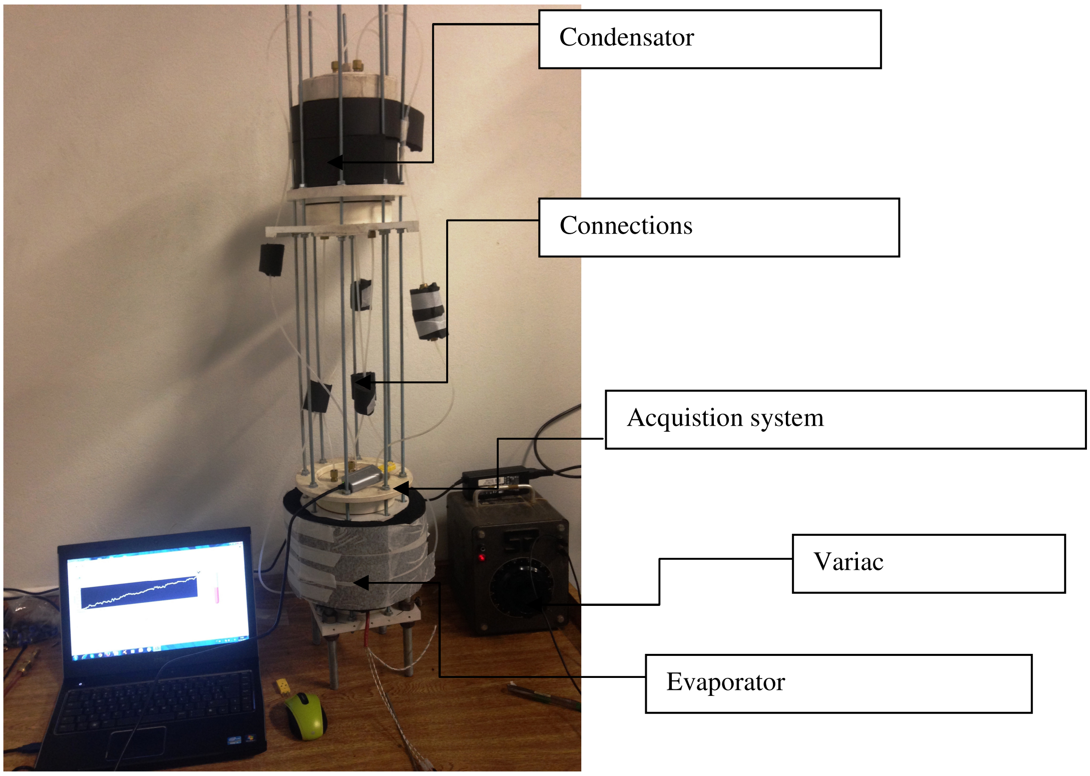

Figure 3. Complete experimental system

The water in the evaporator was heated with an electrical resistance heater, up to the desired temperature around 50 ^{o}C. The cold water in the condenser was kept always at 0 ^{o}C using ice mixed with water. The heater was turned off after reaching the desired temperature, letting the water be cooled by the pulsating heat pipe which connected the two reservoirs. The pulsating heat pipe transferred heat from the evaporator to the condenser. The temperature of both reservoirs was measured with thermocouple inserted in the reservoirs. A data acquisition system (Labview, 2007) was used to register the temperature variation of the evaporator along time. The heat transfer rate was determined by energy balance along the evaporator.

2.2 Data reduction procedure

Equation 1 was used to estimate the heat transfer rate transferred by the pulsating heat pipe.

$$Q = m_{water} \cdot c_{water} \cdot \frac{\Delta T}{t} \tag{1}$$

where:
Q: heat transfer rate in Watts,
m_{water}: water mass in the evaporator
c_{water}: specific heat for the water 4180 J/kg.K,
ΔT: temperature difference in the measured time interval,
t: time interval in seconds.

For determination of the total thermal resistance of the pulsating heat pipe Eq.2 was used.

$$R_{tot} = \frac{T_{evap} - T_{cond}}{Q} \tag{2}$$

where:
R_{tot}: total thermal resistance of the pulsating heat pipe in °C/W,
T_{evap}: water temperature in the evaporator, °C,
T_{cond}: water temperature in the condenser, °C.

The equivalent thermal conductivity of the pulsating heat pipe was determined by use of Eq. (3). This parameter allows comparison of the performance of the heat pipe against other conductive materials.

$$K_{eq} = \frac{Q \cdot L}{A_c\left(T_{evap} - T_{cond}\right)} \tag{3}$$

where:
K_{eq}: equivalent thermal conductivity, W/m.k.
L, distance between the evaporator and the condenser, m.
A_c: total tube cross section area in the adiabatic region of the pulsating heat tube.

To account the effect of heat losses from the evaporator to the environment an experiment without the pulsating heat pipe working was performed. In this test, hot water in the evaporator was let to cool and the water temperature decay along time was used to estimate the heat losses through energy conservation. The evaporator heat losses was estimated to be 6 W. This heat loss was subtracted from the heat transfer rate, Q, to obtain the effective heat transfer rate, Q_{eff} (W).

3. RESULTS

The experiments were performed for three different inclination angles: 90° (vertical), 50° and 20°. Figures 4 to 6 shows the evaporator temperature and heat transfer rate along time.

- <u>90° Inclination</u>

As showed in Fig. 4 the pulsating heat pipe obtained the follow results: average heat transfer rate Q=43.5 W, effective average heat transfer rate Q_{eff}=37.5W, average equivalent thermal conductivity K_{eq}=25520 W/m.K and average total thermal resistance of R_{tot} =0.80 °C/W.

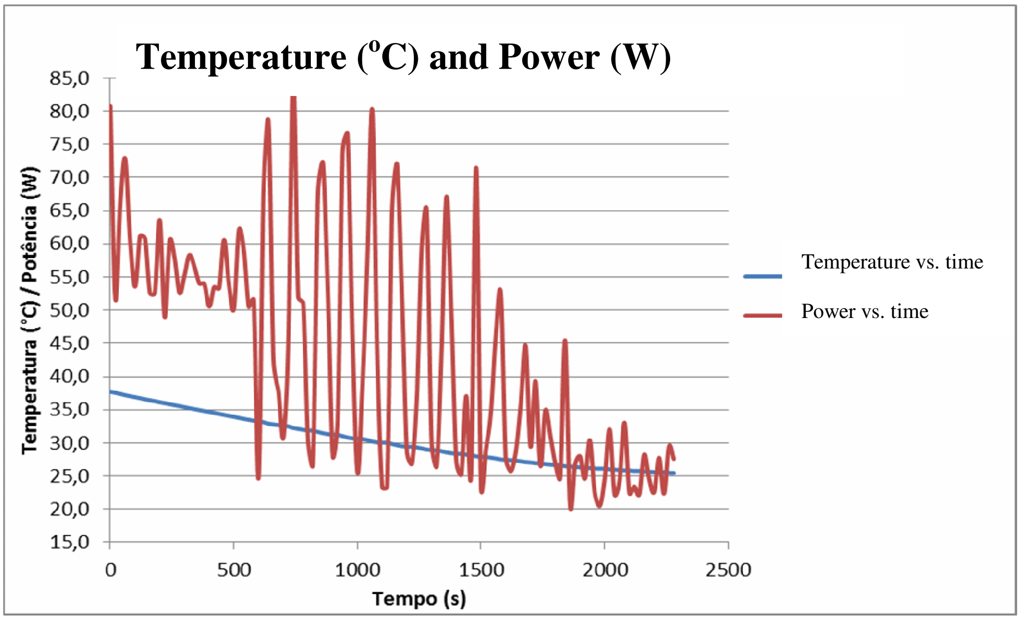

Figure 4. Evaporator temperature and pulsating heat pipe heat transfer for 90° inclination angle.

- 50° Inclination

As showed in Fig. 5 the pulsating heat pipe obtained the follow results: average heat transfer rate Q=37.4 W, average effective heat transfer rate Q_{eff} = 31.5W, average equivalent thermal conductivity K_{eq}=21955 W/m.K and average total thermal resistance of R_{tot} =0.87 °C/W.

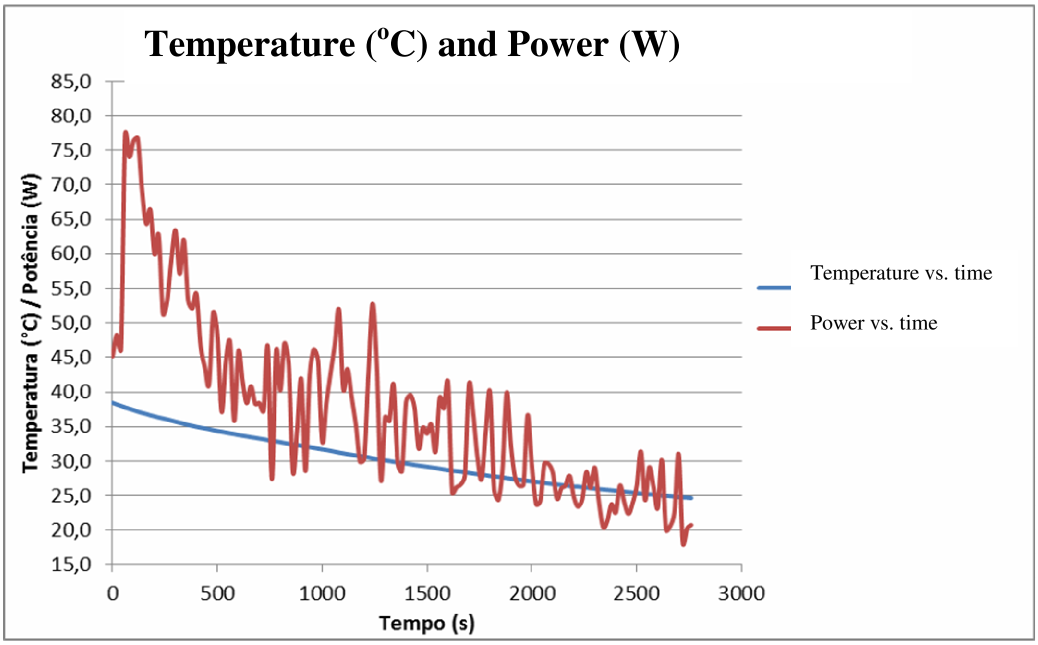

Figure 5 Evaporator temperature and pulsating heat pipe heat transfer for 50° inclination angle.

- 20° Inclination

As showed in Fig. 6 the pulsating heat pipe obtained the following results: average heat transfer rate Q=35.7 W, average effective heat transfer rate Q_{eff} = 29.7W, average equivalent thermal conductivity K_{eq}=20340 W/m.K and average total thermal resistance of R_{tot} =1.00 °C/W.

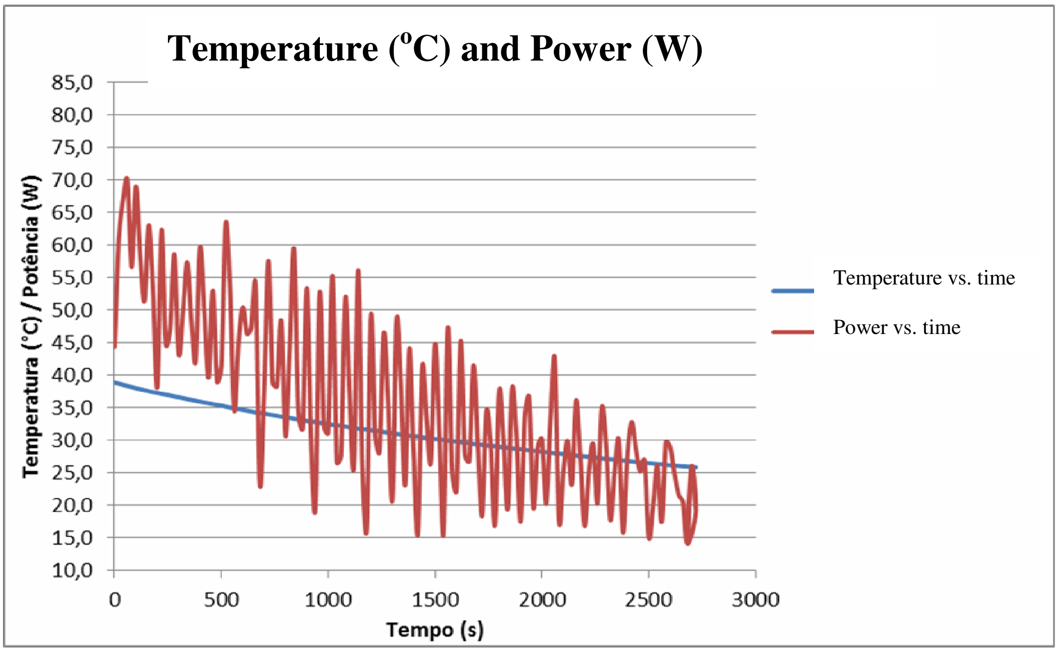

Figure 6. Evaporator temperature and pulsating heat pipe effective heat transfer for 20° inclination angle.

Analyzing all results, summarized in Table 1, it can be observed that the immersed area in the evaporator and in the condensator is an important parameter in the design of pulsating heat pipes. Increasing the immersed heat transfer area by a factor of 5 the heat transfer increased around 3 times.

Changing the inclination from 90° to 20° reduced the performance of the tested heat pipes around 20%, showing that these pulsating heat pipes can work effectively for a wide inclination range. For inclination angles below 15 ° the tested pulsating heat pipes stopped of working, showing that gravity forces are still important for this tube diameter of 2.0mm. Returning the inclination above 20° the flow restarts almost instantantly.

Table 1. Comparative results for immersed length of 1 m and 5.5 m.

Immersed length 1.00 m		
Inclination 90°	Inclination 50°	Inclination 20°
Power (W)	Power (W)	Power (W)
17,50	14,80	11,70
Kequiv (W/m.K)	Kequiv (W/m.K)	Kequiv (W/m.K)
19780,00	16700,00	13340,00
Resist.	Resist.	Resist.
1,95	2,30	2,45

Immersed length 5.50 m		
Inclination 90°	Inclination 50°	Inclination 20°
Power (W)	Power (W)	Power (W)
43,50	37,40	35,70
Kequiv (W/m.K)	Kequiv (W/m.K)	Kequiv (W/m.K)
25520,00	21955,00	20340,00
Resist.	Resist.	Resist.
0,80	0,87	1,00

4. CONCLUSIONS

A new configuration of pulsating heat pipe using polymeric material filled with R134a were developed and tested. The main conclusions obtained from the experiments are:

- Pulsating heat pipes using polymeric materials work properly and obtained high effective in thermal performance.
- The measured equivalent thermal conductivity of the pulsating heat pipes reach 25520 W/m.K, the total thermal resistance 0.8 °C/W for a heat transfer ration up 37.5 W.
- Nylon performed well as wall material with the advantage of be a low cost material and to be very flexible which are important for applications.
- The pulsating heat pipe worked for horizontal angle above 15°, and between 20° to 90° the performance increased by 20%.
- The results showed the potential of applying flexible polymeric materials to build pulsating heat pipes which allows versatile heat exchanger design in applications with complex geometries and compact needs.

5. ACKNOWLEDGEMENTS

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